Driving Application: Liver Ablation

- Hepatocellular Carcinoma (HCC): 1M cases per year (worldwide)
- The most frequent hepatic malignancy in USA is metastatic disease from colorectal cancer
- Resection -- 5 year survival rates between 25% and 55%
- Most patients do not qualify for resection
- un-resectable liver tumors are ablated under ultrasound guidance

Thermal Ablation of Liver Tumors

Problems with the Free-Hand Approach

- Dependent on physician accuracy
- Often requires multiple passes
- Unsuccessful ablation rate = 5%
- Inconsistent
- Not repeatable
- Post-ablation evaluation

Disclaimer

- Overview and understanding, not comparison
- Not every possible work will be discussed (lack of time)
- Not every group or individual will be covered (lack of time)
- There is no financial interest with the companies mentioned in this presentation
Situations in Which 3DUS Guidance May Be Most Useful

- Large Tumor with Small Ablation Zone
- Irregular Shaped Lesions

Proposed Solutions

- Passive / Passive
  - Freehand 3D Ultrasound
  - Passive arm for needle

- Passive / Active
  - Freehand 3D Ultrasound
  - Robot Needle Placement

- Active / Passive
  - Robotic 3D Ultrasound
  - Passive arm for needle

- Active / Active
  - Robotic 3D Ultrasound
  - Robot Needle Placement

A Dual-Armed Robotic System

Ultrasound Calibration

Closed form formulation

\[ B = B_2^{-1} B_1 \]
\[ A = A_2 A_1^{-1} \]
\[ AX = XB \]

Patient Specific in vivo Calibration

If only we could estimate "A" without phantom...

AX = XB
Ablation under US Guidance is Blind

Elastography (Pioneered by Ophir, Sarvazyan, Bamber, Varghese, Hall, Emelianov, …)

Stress–Strain Measurements
- Elasticity changes are immediate and permanent
- Cooked and raw liver can always be told apart
  - Young’s modulus ratio is ~10
- Stress is linear below ~5% strain

Ex vivo Imaging Study
- Supporting gelatin
- Fiducials markers in transparent gelatin
- Radionics single-rod ablator device
- Ellipsoidal ablation along the needle shaft
- Large ablation in short time by using cool-tip technology

2D representation of strain based imaging model. Before compression: the overlay represents 1D cascaded particles with uniform spacing. After compression: the overlay represents two groups of particle spacing. Small spacing (light green) indicating soft tissues moved more (high strain) than the hard tissue (low strain).
Registration between Elasticity Image and Gross-pathtology

- Supporting gelatin
- Fiducials markers in transparent gelatin
- Radionics single-rod ablator device
- Ellipsoidal ablation along the needle shaft
- Large ablation in short time by using cool-tip technology

The Liver Samples

- 4 Min
- 6 Min
- 8 Min

Strain Results

B-mode image shows ex-vivo liver boundaries embedded in gel based medium. It is not possible to differentiate the ablated area from B-mode. Strain is generated from differentiating a displacement map in the axial direction. Strain provides clear evidence of the presence of hard lesion, which is in agreement with the gross pathology picture.

Serial Segmentation Pipeline
Elasticity-based Segmentation

- B-mode image
- Displacement image
- Correlation image
- Displacement estimate
- Boundary conditions
- Geometric mesh
- Elasticity map
- FEM
- Model displacement conditions

\[ \rho \frac{\partial^2 u}{\partial t^2} - \nabla \cdot (c \nabla u) = K \]

Navier’s equation

Elasticity-based Segmentation

Moving from ex vivo to in vivo

- Real-time strain imaging or rapid interactive rate
- Robustness to uncontrolled motion
- High resolution, SNR and CNR
- 2D (or 3D) extension
- High axial compression
- Insensitivity to signal decorrelation

\[ S = \arg \min \{ S \} = \sum_{i=1}^{N} \sum_{j=1}^{M} W(i,j) \| u(i,j) - u(i,j;S) \|_2 \]
Dynamic programming approach

Amplitude similarity
\[ \Delta(i, d) = |y(i) - y'(i + d)| \]

Smoothness
\[ S(d_i, d_{i-1}) = (d_i - d_{i-1})^k \]

Recursive cost function
\[ C(i, d_i) = \min_{d_{i-1}} [C(i - 1, d_{i-1}) + wS(d_i, d_{i-1}) + \Delta(i, d_i)] \]
\[ M(i, d_i) = \arg \min_{d_{i-1}} [C(i - 1, d_{i-1}) + wS(d_i, d_{i-1})] \]

Contrast to Noise Ratio
\[ CNR = \frac{C}{N} = \sqrt{\frac{2(c_x - s_x)^2}{\sigma_x^2 + \sigma_b^2}} \]

- Target window is fixed on the lesion
- Background window is moved across the strain image

Dynamic Programming Elastography vs. Normalized Cross-correlation Methods

2D Dynamic Programming Elastography


- Rivaz et al., TMI 2008.
Freehand Palpation of Resected Prostate

NCC

Higher Strain

DP

Malignant Tumor

In vivo Patient Studies

ultrasound elasticity post-operation CT

patient 1

thermal lesion not visible thermal lesion visible!!

patient 2

Rivaz et al., MICCAI 2008

Challenges and Possible Solutions

• From 2D to 3D displacement
• Effective and rapid visualization
• Optimal real-time elasticity imaging
• Large animal model for in vivo validation

3D Elasticity Imaging of Ablation

experimental setup pathology

ultrasound images, After 10 min

elasticity images, After 6 min

elasticity images, After 10 min

Rivaz et al., MICCAI 2008
Elasticity-based Volume Rendering of 3DUS B-mode data

Preparation
- Strain data

Preparation
- 3D ultrasound data

Shading
- Ray tracing
- Resampling

Sample opacities
- Voxel opacities
- Voxel colors

Ray-tracing / resampling
- Sample colors
- Sample opacities

Compositing
- Image pixels
- Render pixels

Ray Casting Volume Rendering Pipeline Based on Strain Data as Opacity Volume

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